I D INFLUENCE OF TIME ON STRESS-STRAIN-STRENGTH
BEHAVIOR OF CLAYS DURING UNDRAINED SHEAR

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IID: INFLUENCE OF TIME ON STRESS-STRAIN-STRENGTH BEHAVIOR OF CLAYS DURING UNDRAINED SHEAR

1. INTRODUCTION

1.1 Definition

1) Prior to shear
   a) At constant w (UU): thixotropy
   b) At constant $\sigma'$ (CU, CD): "aging" = secondary compression

2) During shear (undrained)
   a) Rate of strain, $\dot{\varepsilon}$, as increase $\dot{q}$
   b) Time after applying constant $q$ = creep
   c) $\ldots$ $\ldots$ $\ldots$ $\varepsilon$ = relaxation

1.2 Discussion on Drained Behavior

- For drained shear, $\varepsilon$ (or $\dot{q}$) believed to have
  little effect on $c'$, $\phi'$ for "ordinary" clays.
- But not for highly structured cemented clays - see Section 4.4


2.1 Definition

- With some clays, if remold and then store at constant composition $\rightarrow$ min. stiffness & strength
- Thixotropy = isothermal, reversible, time-dependent process occurring under conditions of constant composition & volume whereby a material stiffens while at rest and softens on remolding.
2.2 Behavior Measured in UWE Tests

1) Based on limited published data.

- PHD Berkeley on swelling of clay
- SM MIT UWC ~1960±
  (But not Oun, BS)

2) Comments
- Storing disturbed tube samples may → inc. $S_u$ of $t$
- No correlation $TSR = S_u(t)/S_u(R)$ and soil type, but restricted to clays and generally more important with increasing $I_e$

2.3 O'Neill (1985) - Behavior of Block Samples of Resedimented BBC II

1) See p2a for dedrite:
   $\sigma'_p \propto \log t_3$ ($t_3 =$ strain time)
   - 1 week → $\sigma'_p = 1.1$ (expected)
   - 3 mm → $\sigma'_p = 1.35$
   - 2 yr → $\sigma'_p = 1.9$

2) During this period
   - $\Delta W \approx 0$
   - Very little increase $I_e$
   - Consistent increase in $\phi$ Recompresion CKUCE of same magnitude $\phi$ largely due to $\Delta I_e$

(see p2a)
O'Neil (1985) Recompression CK0 UV C/E Resed. BBC

OCR = f pum to theisopy

\( \sigma_{vc} = 0.25 \text{ksc} \)

Incr. \( \gamma \) = Incr. \( q_f \)

\( \gamma \) yield show

**NOTE:** Incr. \( \gamma \) largely due to reduced \( \Delta u - \Delta u_{act} \)

\[ u_s = \Delta u - \Delta u_{act} \]

\[ \Delta q_f, \Delta u_s \text{ C/F} \]

"Isotropic" Effect

\[ \Delta q_f, \Delta u_s \text{ C/F} \]

\[ t_3 (\text{days}) \]
2.4 Possible Mechanisms

1) Realignment of clay particles (Mitchell, 1976/1979)
   from "dispersed" → "flocculated" (of fabric and interparticle forces)
   - Presumably \( A > R \) and/or \( \bar{D}_a > \bar{D}_g \)
   - Berkeley data supposed to show that
     occurs in compacted clay → large increase in k

2) Water "structure": Decrease in free energy
   of adsorbed H2O → decreasing n → increasing \( \sigma_0 \)
   - CCL liked before BBC data became available

3) "Bug" (ETM)

4) Conclusions: Mechanism(s) unknown

3 AGING = SECONDARY COMPRESSION

3.1 Review from Treatment of Consolidation

![Diagram showing consolidation process with equations]

\[ \log \frac{\sigma_0'}{\sigma_0} = \frac{C_{d,e}}{C} \log (\frac{d}{b}) \]

Given "fact" (à la Meari) that \( C_{d,e} / C = 0.045 \pm 0.015 \)
for most cohesive soils (both OC/NQ)
- Only important at low OCR (i.e., 'high' C 'high' C)
- Should not vary in consistent fashion
  with changes in Ip
  - Tokyo Fig. 39 very suspect
3.2 Influence on CAUC Tests (OCR=1)

(Pennock 1963; Ladd 1965; Varis & Camporelli 1970)

Note: Aging at constant Ke

1) Aging leads to:
   a) Modest increase in $q_{vc}$, say $5-7\%$ /day $t_c$
   b) Larger increase in $E_u/\sigma_{vc}$ (Ladd 1965 reports $60\pm 10\%$ /day $t_c$ from CAUC test)
   c) Perhaps decrease in $E_u$

2) If same $E_u = E_a$, then:
   a) Same shear induced $E_u = \Delta u - 0.50\sigma_{ec}$ (consistent with ini. OCR)
   b) Increase result in same contacts since same $E_u / E_a$ implies same deformation at contacts

3) Behavior of aged vs. mechanical precompression at same OCR?
   Aging probably $\rightarrow$ stiffer initial response ($E_u$ higher $E_a$)

3.3 MIT Standard Practice for SHAWSER Testing

Perform CKoU tests after $t_c = 1$ day ($\log t_c / 1$ day $= 1$ log cycle)

1) Minimize $\Delta u$ due to "stopping" secondary compression
2) Standard $t_c$ $\rightarrow$ more consistent data
3) To install some "structure" in the clay (i.e., make stiffer) that was destroyed by consolidating beyond ini. OCR

NOTE: Empirical aspect of SHAWSER. Also actual OCR is slightly higher than reported (since aging increases $\sigma_{vc}$)
3.4 Influence of Consolidation Time on CKBoss Data

1) As per 3.3, SHERER CKB tests typically use \( t_c = 1 \) day at \( \sigma_{vc} \) (\% of \( \sigma_{vm} \)) when attempting to predict undrained shear strength behavior of naturally OC clays.

2) However, during staged construction, foundation clay is still undergoing consolidation, i.e., presumably lies on \( t_c \) (EOP) compression curve. Therefore, there will not be any "aging" (secondary compression).

3) Following compares \( t_c = 1 \) day vs. \( t_c = 2 \) hr ("EOP") for two plastic soils at peak strength (each average of 2 tests) at \( \dot{\gamma} = 5 \% / \text{hr} \)

<table>
<thead>
<tr>
<th>Soil</th>
<th>( t_c )</th>
<th>( V_f(%) )</th>
<th>( T_h / \sigma_{vc} )</th>
<th>( T_h' / \sigma_{vc} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Kills, NY Organic Silt (( I_p = 60% ))</td>
<td>1 day</td>
<td>14.5 ( \pm 0.5 )</td>
<td>0.296 ( \pm 0.018 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 hr</td>
<td>14.1 ( \pm 4.9 )</td>
<td>0.257 ( \pm 0.020 )</td>
<td>( -13% )</td>
</tr>
<tr>
<td>Sargipá, Brazil Offshore CH (( w_e = 65% ))</td>
<td>1 day</td>
<td>9.4 ( \pm 0.2 )</td>
<td>0.2385 ( \pm 0.0035 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 hr</td>
<td>7.6 ( \pm 0.9 )</td>
<td>0.2163 ( \pm 0.0167 )</td>
<td>( -9.3% )</td>
</tr>
</tbody>
</table>

\[ \Delta\sigma_{vc} = -10.5\% \]

Note: For \( \dot{\gamma} = 0.5 \% / \text{hr} \), reduction \( \rightarrow -11.8\% \)

4) Effect is significant. Therefore should use \( t_c = t_p \) (EOP) to obtain \( \sigma_{vc} / T_h' \) for OCR = 1 "undrained" soil.
4. EFFECT OF STRAIN RATE

4.1 Overview:

- Overview of CPTU, Lab TV, PP
- Trends from in-situ tests and Lab UU & CU tests

\[ \frac{S_u}{S_{u0}} \]

- Definition of parameters
- Equation for strain rate

2) Reported values of \( P \) and comments:
   - Most of the early (<1970) data came from UUC tests → unknown OCR
   - Most CU data with known OCR from CIVC tests

   \[
   \begin{align*}
   NC & \quad \text{Typical } P = 10 \pm 5 \% \; ; \; t_f = 1 \text{mm} - 1 \text{ week} \\
   \text{High OCR} & \quad \text{Typical } P = 15 \% \; ; \; t_f = 5 \text{mm} - 1 \text{ week}
   \end{align*}
   \]

   [Note: Undisturbed CL-MC Hong Clay, CKvUC at OCR > 10 \rightarrow P = 30-35%]
   (Andersen & Shankweiler, 7/82, JGE)

3) Implications when comparing \( S_u \) data having different \( t_f / \varepsilon \):
   - Compare UUC at \( \varepsilon = 12 \text{mm} \) vs. CKvUC at \( \varepsilon = 0.52 \text{mm} \) → 2 log cycles
   - \( \Delta t_f = 20 \pm 10 \% \) for \( P = 10 \pm 5 \% \) at low OCR
     \[ \text{Typical } P = 30-60 \% \text{ at high OCR} \]

4) Extreme case: Offshore Alaska at Smith Bay; CL-CH Fluvioxic Clay
   - \( N_k = 15 \)
   - \( S_u \) (UUC, FV) \& CPTU \( \approx 3 \times S_u \) (DSS)
   - From SHANSEP mix well defined
     \[
     \frac{S_u}{S_{u0}} \quad \text{or} \quad S_u \text{ profile}
     \]
   - \( S_u \) (UUC, FV) \& CPTU
   - Young (1986) MIF
   - Jardine

5) Special case: Urban site, high OCR, low strain rate, low OCR
4.2 Results from CIUC Tests at High OCR: Fixed End Caps

**NOTE**: Also applies to UUC testing at varying $e$

1) Overview of problem (also see Notes on measurement of $e'$, $f'$, $I_B$)

![Graph showing shear stress vs. strain](image)

2) Results on OCR = 16 CH clay [Richardson & Whitman 1963, Test 13(4) + OCL CIUC with $u_m$ (at middle + correct ESP)]

3) Conclusions:
   a) Regular CIUC/CV tests at varying $e$ on high OCR clay are partially drained; hence $du$ in $u_e$ at slower rates due to softening of shear zone.
   b) Need lubricated end caps to measure correct $du_e$ on $OCL$.
   c) Will in situ shearing of high OCR clay also result in softening of potential shear zone, and hence lower $u_e$?

CCL doesn't know, but probably possible (need to study lubrication).
4.3 Results from CK_oUC Test on RBBC at OCR = 12.41:
Lubricated End Caps and Mid-Specimen U Data

[Sheahan 1991 MIT PhD thesis; Sheahan et al., 1996, JCE, 122(2)]

1) Test Program
- 1st MIT automated TX cell, $E = 0.05, 0.5, 5 \text{ kPa}$
- Cell fluid = oil to prevent membrane leakage

2) Behavior at strain $E = 0.5 \text{ kPa}$
- See Fig 1/8
- Note that data normalized to $0\%$

Typical normalized shear stress and excess pore pressure versus strain for CK_oUC tests on resedimented BBC at reference strain rate ($\epsilon_a = 0.5\%/h$)

Typical normalized effective stress paths for CK_oUC tests on resedimented BBC at reference strain rate ($\epsilon_a = 0.5\%/h$)

Figures by MIT OCW.
3) Overview of effects on $s_u$

a) $s_u/\sigma_{vm}$ vs $\log \dot{e}$ at $(OCR) \# Fig 11$

$\dot{e} = 0.05$

\[ \text{Zone A} \quad \text{Zone B} \quad \text{Zone C} \quad 50\% h \]

$J_{ov}$ = (Fast to Very Fast)

- Get effect at all OCR that $\dot{e}$ is a constant
- $\dot{e}$ is 9.6 $\pm$ 2.0

$J_{ov}$ = (Slow to Fast)

- $\dot{e}$ decrease with increasing OCR (plot data to show this!)
- $\dot{e}$ goes to zero with increasing OCR more rapidly at least $83\%$ range.

\[ \text{Normalized shear strength versus strain rate CK}_{/C} \text{ tests, resedimented BBC} \]

Figure by MIT OCW.

b) $\log s_u/\sigma_{vm} = \log OCR + f(\dot{e})$ Table 4

<table>
<thead>
<tr>
<th>Strain rate $\dot{e}$ (%/hr)</th>
<th>$s^*$</th>
<th>$m^*$</th>
<th>$f^*$</th>
<th>Number of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.298</td>
<td>0.737</td>
<td>0.9997</td>
<td>6</td>
</tr>
<tr>
<td>0.5</td>
<td>0.320</td>
<td>0.714</td>
<td>0.9993</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>0.346</td>
<td>0.689</td>
<td>0.9997</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>0.377</td>
<td>0.656</td>
<td>0.9984</td>
<td>8</td>
</tr>
</tbody>
</table>

- $s^*$ = value of $\dot{e}_u/\sigma_{vm}$ at OCR = 1, based on regression analysis.
- $m^*$ = strength increase exponent (refer to Eq. (3)).

\[ \text{~Complex trends} \]

- Slow $\rightarrow$ Fast $\dot{e}$ $\rightarrow$
  - Increasing $S$ $\rightarrow$ decreasing $m$
- Fast $\rightarrow$ Very Fast $\dot{e}$ $\rightarrow$
  - Increasing $S$ at constant $m$
4) Overview of effects on shear-strain + ESP behavior

a) Shear strain vs $\varepsilon_a$
   - See Sheet A1/A2 for $q/\varepsilon_a = \varepsilon_a$ = very constant trend.
   - Fig 12 of Sheet B shows that normalized $q_2/q_3 = \varepsilon_a$ is unique at OCR = 2.478 (very important for soil modeling).
   - Post peak behavior at OCR = 1 is scattered.

b) Pre-pressure vs $\varepsilon_a$
   - Look at shear induced: $\Delta u_s = \Delta u_2 - \Delta u_1 = \Delta u - \frac{1}{3} \Delta q_2 = \varepsilon_a$
     - On Sheet A1/A2.
     - Increase in $\varepsilon_a$ are always accompanied by lower $\Delta u_2$.
       (Also see Fig 13a, Sheet B), e.g.
       - OCR = 1, increasing $\varepsilon \rightarrow$ incr. $u_s$ 1 decr. $\Delta u_2$.
       - OCR = 8, $\varepsilon = 0.05$ to $5$, $\Delta u_2 = 0 \rightarrow$ no change in $\Delta u_2$.

c) Effective stress paths and failure envelopes
   - See Sheets A1/A2 for ESP - consistent trends.

\[ \frac{q}{q_{um}} \uparrow \]
\[ \frac{\sigma}{\sigma_{um}} \downarrow \]

\[ OCR = 1.32 \rightarrow \text{Low OCR: increased } u_s \text{ due to both lower } u_s \text{ and higher ESE (C)} \]
\[ OCR = 4.18 \rightarrow \text{High OCR: increased } u_s \text{ due only to lower } u_s \text{ (same ESE)} \]

---

**Note:** The diagram shows the relationship between effective stress and strain, with OCR affecting the behavior.

---

**Further Reading:** For detailed analysis and calculations, refer to Sheets A1/A2 and Sheet B.
4.3 Cont

5) Summary of CKDV testing program on RBCC (practical implications for non-structured clays)

a) Very fast shearing to increased 5e that is 5 constant
   at all OCR (Po5 < 10%). Applies to in situ testing / lab OCR, etc.

b) At slower strain rates, shear rate sensitivity (Po5 > 0)
   decreases with increasing OCR.

Hence for field loading, would not expect design of
moderate to high OCR clays to be < measured lab CKDV test


c) Shear rate sensitivity (increases in e with incre 5e) is caused
   by two mechanisms:
   1) Increasing 5e 5 decreasing OCR : Occurs at all OCR
   2) Increasing 5e 5 remain in SSE at peak strength : Occurs only at
      low OCR
   * at OCR < 2, Po5 due to both decreased OCR & min 5e
   * at OCR > 2, Po5 due only to decreased OCR

   d) At OCR > 1, obtain unique 5e/50.5e vs e at independent of 5e
      (simplified modeling)
4.4 Behavior of Highly Structured (Cemented-Sensitive) vs "Ordinary" Clays

1) Observations from 1-D Consolidation Data

Hypothesis A
- Unique $E_{1} vs \log \sigma_{vc}'$ during primary, i.e., independent of $q$
- Appears reasonable for saturated clays of low-modulus $G$
- Same mechanisms cause creep as occur during primary
- e.g., slippage at particle contacts

Hypothesis B
- Unique $E_{1} = \varepsilon'_{c} - \sigma_{vc}'$ = same $E_{1} = \log \sigma_{vc}'/\sigma_{p}'(\varepsilon)
- Better model for high $I_{e}$-5$e$ Canadian clays
- "Structural Viscosity" due to time dependent strength of cementation bonds (true cohesion)

2) CU Test Programs at Varying $\varepsilon$ by Lefebvre & Le Boeuf (1987)
- 5 block samples from 3 sites, $I_{p} = 10.23 \pm 10.9$, $I_{e} = 2.3 \pm 0.6$
- $\sigma_{p}' = 140 \pm 45$ kPa

a) CU Tests on INTACT Clay, $\sigma_{vc}' = \sigma_{vo}'$ (see p126)
- Appears same $\Delta u$ vs $\varepsilon$ up to peak $\sigma_{u}$ at $\varepsilon_{f} < 12$, and hence
- Same prefailure ESP
- Lower $\sigma_{u}$ with decr. $\varepsilon$ due to lower yield shear = failure envelope
- Attributed to rate dependent cementation bonds
- "Structural viscosity" of cohesive component (see Benin, 1973)

b) CU Tests on DESTRUCTURED Clay, $\sigma_{vc}' > \sigma_{p}'$ (see p126)
- Decreasing $\varepsilon$ → higher $\Delta u$ : Lower $\sigma_{u}$ due to lower $\sigma_{p}'$
- (and also lower $\sigma_{p}'$ in CAVC tests, see RBBC)

NOTE: Both test series → same $p'$ (Fig.16, p126), but
due to different mechanisms.
Stress strain and pore pressure strain curves for B6 Clay

Stress Paths for Structured B6 Clay

B6 Clay

$\sigma'_{vc} = 72$ to $75$ kPa

$\sigma'_{vo} = 40$ kPa

CAUC Triaxial Tests

Ps CLAY (cm/7.1m Depth)

Figures by MIT OCW.
OLGA CLAY

\[ \sigma'_{vc} = 72 \text{ to } 75 \text{kPa} \]
\[ \sigma'_{vo} = 40 \text{kPa} \]

CAU Tr Duchess Tests

Stress strain and pore pressure strain curves for OLGAClay

Test Symbol Strain Rate (%/m)

\begin{array}{|c|c|}
\hline
\text{Test} & \text{Symbol} & \text{Strain Rate} \\
\hline
\phiL-P 06 & \text{---} & 12.30 \\
\phiL-P 08 & \text{--} & 0.11 \\
\phiL-P 10 & \text{---} & 2.48 \\
\phiL-P 11 & \text{---} & 0.10 \\
\hline
\end{array}

Figures by MIT OCW.

OLGA CLAY

\[ s'_{vc} = 17.7 \text{kPa} \]

CPUC Traxial Tests

\[ \sigma'_{p} = 78 \text{kPa} \]
\[ \varepsilon = 4.1/\text{hr} \]

- Approximately same outcome as up to \( \varepsilon_f \) at peak undrained \( \varepsilon_c \) (especially \( \phi 6 \) - unique \( ESP \) independent of \( \varepsilon \))
- Therefore decrease in \( s_u \) due to lowering of failure envelope, i.e., brittle cementation bonds exhibit "structural viscosity"
Stress-strain and pore pressure strain for normally consolidated B6 Clay

<table>
<thead>
<tr>
<th>Test</th>
<th>Symbol</th>
<th>Strain Rate (%/t)</th>
<th>$\sigma'_v$ (%)</th>
<th>$\sigma'_c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAUCv-04</td>
<td></td>
<td>5.00</td>
<td>269</td>
<td>144</td>
</tr>
<tr>
<td>CAUCv-08</td>
<td></td>
<td>0.5</td>
<td>275</td>
<td>140</td>
</tr>
<tr>
<td>CAUCv-08</td>
<td></td>
<td>0.05</td>
<td>287</td>
<td>144</td>
</tr>
</tbody>
</table>

Figures by MIT OCW.
Stress paths for Normally consolidated Olga Clay

\( \sigma^{'}_{vc} = 1.7 \sigma^{'}_p \)

Figures by MIT OCW.

<table>
<thead>
<tr>
<th>Test</th>
<th>Symbol</th>
<th>Strain Rate (%/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-18</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>p-14</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>p-13</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>p-12</td>
<td>-</td>
<td>12.0</td>
</tr>
</tbody>
</table>

\( \sigma^{'}_{vc} = 137 \text{ kPa} \) c/u Triaxial test

Change of undrained strength ratio, normalized to undrained strength ratio at \( e_1 = 1.0\% \text{/hr} \), with strain rate for all investigated clays.

Same Intact & Destructured
4.5 Concluding Remarks

1) Be aware of most published data on 
\( \varepsilon \) effects due to experimental problems
   - Membrane leakage \( \rightarrow \) increased \( \varepsilon \) due to lower \( \varepsilon \)
   - End restraint at high OCR \( \rightarrow \) softening in shear zone \( \rightarrow \) decreasing \( \varepsilon \)
   - If very low to, allowed \( \varepsilon \) due to secondary compression may \( \rightarrow \)
     Confidently \( \Delta \varepsilon \neq 0 \) (e.g., Helgeson et al. 1973 CSJJ, OUC test on SBM)

2) It is likely that all cohesion soils will exhibit strain rate sensitivity
   at very fast strain rates (say \( \varepsilon \) > 5×10⁻³/𝑠) that will affect
   interpretation of in situ tests and lab OCR, TV, etc. tests. Can get very high \( \varepsilon \)
   10-30%

3) For non-structured clays similar to Resedimented BBS
   Sheahan et al. (1996) present the only good CK, OUC \( \varepsilon \) strain rate effects
   data as \( f(OCR) \). Principal conclusion are (in \( \varepsilon \) ≤ 5%)
   a) At low OCR ≤ 1:
      - \( \varepsilon_{0.5} \) due to both lower OCR and increased \( \varepsilon \)
      - Should expect strain rate effects in field
   b) At moderate to high OCR:
      - \( \varepsilon_{0.5} \) due mainly to only lower OCR
      - Strain rate effects in field may be very small
        \( \varepsilon \) ≤ 10 w/ min, OCR at low \( \varepsilon \)

4) For Canadian cemented clays, expect significant strain
   rate effects in both lab and field on undrained \( \varepsilon \) range
   (in both consolidation and drained/undrained shear)
5. **UNDRAINED CREEP**

5.1 **Introduction**  (Constant \( q \) testing)

1) "Low" stress level (Only" primary")

```
\[ \text{Slope} = \frac{d\varepsilon}{dt} = \dot{\varepsilon} \]
\[ \text{Elastic} = \varepsilon_e \rightarrow t \]
```

- Model with Simh-Mitchell 3 parameter eqn.

2) "High" stress level \( \rightarrow \) Creep Rupture

```
\[ \text{Temporary} = \text{Primary} = \varepsilon \text{ decreasing} \]
\[ \text{Viscous} = \text{Steady State} = \text{Secondary} = \varepsilon \text{ "constant"} \rightarrow \varepsilon_m \text{ (Inflation point of creep rupture)} \]
\[ \text{Tertiary} = \varepsilon \text{ increasing} \rightarrow \text{creep rupture} \]
```

3) **Questions**

- Physical explanation of behavior (if possible)
- Mathematical models of behavior, at least for primary
- How to estimate \( q \) that will not \( \rightarrow \) creep rupture (lengthy long term \( q \))
- "Correspondence" between creep \& constant \( \varepsilon \) test data.

1) Eqn.
    \[ \dot{\varepsilon} = A e^{\frac{2 \bar{D}}{t_{i/t}}^m} \]

   - "Derived" from Rate Process Theory
   - Restricted to Primary creep

\[ \frac{t_i}{t} \text{ reference time} \]
\[ \bar{D} = \frac{d \ln \dot{\varepsilon}}{d \ln t} \text{ (diff. at reference \( \dot{\varepsilon} \))} \]
\[ m = -\frac{d \ln \dot{\varepsilon}}{d \ln t} \]
\[ \alpha = \frac{d \ln \dot{\varepsilon}}{d \bar{D}} = \frac{2.3 \ln \dot{\varepsilon}}{d \bar{D}} \]
\[ A = \dot{\varepsilon} \text{ at } t = t_i, \bar{D} = 0 \]

2) Basic plots

   ![Log-log plots](image)

\[ \bar{D} = \frac{d \ln \dot{\varepsilon}}{d \ln t} \]
\[ \text{Incr. } \bar{D} \]
\[ \alpha \text{ presumed constant for } \bar{D} = 0.3 - 0.9 \]

3) Significance of \( m \) (Presumed basic soil property by S-M)

- Lower \( m \) → More creep susceptible

\[ m = 1 \rightarrow \dot{\varepsilon} = \text{constant} \]
\[ (\text{like constant } C_D) \]

\[ m < 1 \text{ more "creep susceptible" d/a S-M} \]

\[ w/ \dot{\varepsilon} \text{ increasing w/ } t \]

\[ \dot{\varepsilon} = \dot{\varepsilon}_1 - \frac{A e^{\frac{2 \bar{D}_i}{t}} + \dot{\varepsilon}_t}{(1-m)} \quad \text{for } m \neq 1 \]

Slope - \( \frac{d \dot{\varepsilon}}{d t} = \frac{0.434}{t} \cdot \frac{d \dot{\varepsilon}}{d \log t} \)
4) Results from MIT research on flood control levees along Atchafalaya River in Louisiana next to Gulf of Mexico (Edguy et al. 1975 MIT Report)

a) Problem (EABPL)

b) Results from creep testing on EABPL clay

<table>
<thead>
<tr>
<th>Test</th>
<th>D</th>
<th>m</th>
<th>( \bar{\tau} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0C</td>
<td>0.75-0.9</td>
<td>0.95</td>
<td>4.7</td>
</tr>
<tr>
<td>NC</td>
<td>CKUC</td>
<td>0.5-0.9</td>
<td>0.55±0.1</td>
</tr>
<tr>
<td></td>
<td>CKWDS</td>
<td>0.5-0.85</td>
<td>0.85±0.9</td>
</tr>
</tbody>
</table>

\[ m = 0.55 \text{ to } 0.95 \]


- CIUC \( m = 0.6 \)
- CKUC \( m = 0.35 \)
- CKWPS \( m = 0.5 \)

\[ m = 0.35 - 0.6 \text{ for clay that is not very creep susceptible} \]

6) Conclusion

a) However, e.g., soil useful for modeling ground of primary creep data

b) Value of \( m \) is not valid criterion for creep susceptibility,

\[ \text{e.g., lower } m \text{ does not mean more highly creep susceptible} \]

(see section 5.6 for new criterion)

c) Techniques do NOT exist to predict undrained creep in the field (even though S-Moehn has been added to MCI to do this, e.g., Borja et al. 1990, J.GE. 116(9))

5.3 Creep Rupture

1) General Behavior: Results from creep test run at varying $\bar{D} = 0.8/0.8t$

![Graph showing creep rupture and strain rate vs. time]

- For test at $\bar{D}$
- Creep rupture
- Really an inflection point at $\bar{D}$

2) Strain at Minimum Strain Rate ($\dot{\varepsilon}_m$)
- Experimental data show approximately constant strain ($\dot{\varepsilon}_m$) along the $\log \dot{\varepsilon}_m \text{ vs. } \log t_m$ relationship
- $\dot{\varepsilon}$ is decreasing before reaching $\dot{\varepsilon}_m$, and then accelerates after reaching $\dot{\varepsilon}_m$. This suggests that "damage" starts to occur near $\dot{\varepsilon}_m$, leading to a weakened material that eventually fails in creep rupture.

3) Creep Rupture Data on Haney Clay (Sheet C1)
- Fig. 2 shows log $\dot{\varepsilon}_m \text{ vs. } \log t$ data from CIUC, CRUC, and CKC/USC tests on NC clay → 3 different log $\dot{\varepsilon}_m \text{ vs. } \log t_m$ relationships
- Fig. 3 shows constant $\dot{\varepsilon}_m$ for each test series. However, $\dot{\varepsilon}_m$ decreases from $\dot{\varepsilon}_m = 2.8$ for CIUC tests to $\dot{\varepsilon}_m = 0.3$ for CRUC tests.
1) Log $\dot{E}_m$ vs. log $t_m$ and $\dot{E}_m$ Data for Other Materials (Sheet C2)

- Fig. 1 and 3 show log $\dot{E}_m$ vs. log $t_m$ data from unconfined compression tests on frozen Manchester fine sand (ICE saturation $E_i = 443$) and polyethylene ICE, respectively, and their unique log $\dot{E}_m$ vs. log $t_m$ relationships
- Fig. 4 summarizes the unique log $\dot{E}_m$ vs. log $t_m$ relationships for frozen MFS ($E_i = 202, 402, 910$), ICE and CIVC/CKC, UC tests on Honey clay.
- Note the shift to the right in log $\dot{E}_m$ vs. log $t_m$ with increasing $\dot{E}_m$ (i.e., increasing $E_m$ -> longer time to reach critical strain at which "damage" -> increasing $\dot{E}$)
- Log $\dot{E}_m$ vs. log $t_m$ can be modeled by $\dot{E}_m = \beta t_m^\gamma$; data in Fig. 4 shows $\gamma = -1.0 \pm 0.2$

5) Summary of Main Points

a) Should plot log $\dot{E}_m$ vs. log $t_m$ from creep tests in order to identify the minimum shear rate ($\dot{E}_m$) at $t = t_m$

b) Creep data from different types of tests (e.g., UC vs. CIVC vs. CKC, UC) and different materials (clay vs. ICE) each show unique log $\dot{E}_m$ vs. log $t_m$ relationships, having a constant $E_m$

c) The $E_m$ represents onset of "damage" that -> increasing $\dot{E}$ and eventual creep rupture

6) Prediction of Creep Rupture

- The literature contains equations 1 plots to predict when creep rupture will occur.

However, the scatter in data for different soils and different types of tests is so large that eqn/plots have little practical significance.
5.4 "Correspondence"

1) This topic addresses the issue between results from constant \( \dot{\varepsilon} \) tests and from creep tests that eventually rupture.

2) Extensive data on polyisobutylene ice (within so-called ductile region with minimal cracking) show a unique relationship between strength and strain rate using \( \dot{\varepsilon} \) in the creep tests, i.e., \( \dot{\varepsilon} = C (\dot{\varepsilon})^{0.293} \) or Power law creep eqn.

![Graph showing relationship between \( 10^9 \dot{\varepsilon} \) and \( \dot{\varepsilon} \) with data points from both constant \( \dot{\varepsilon} \) tests and creep tests.]

3) There are little data on clays comparing constant \( \dot{\varepsilon} \) and creep testing. However, results from Henry clay (see sheet 2) also show correspondence when use \( \dot{\varepsilon} \) in creep tests.

![Graph showing relationship between \( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_c} \) and \( \dot{\varepsilon} \) with data points from both constant \( \dot{\varepsilon} \) tests and creep tests.]

4) Conclusion:

- Use \( \dot{\varepsilon} \) from creep tests for comparison with \( \dot{\varepsilon} \) from constant \( \dot{\varepsilon} \) tests.

5.5 Relaxation

1) Refers to decrease in $q$ (relaxation) at constant strain after shearing at constant $\varepsilon_0$ up to the relaxation strain level ($\varepsilon_r$)

2) Overview of CKoVC data from Sheahan et al. [1994, ASTM, G7717(4)] on reconsolidated OBC (part of test program discussed in Section 4.3)

$\varepsilon_r$ = start of relaxation

- For fast shearing to $\varepsilon_r$, relaxation starts quickly
- For slow $\varepsilon_0$ to $\varepsilon_r$, start of relaxation is delayed

- For relaxation from relatively small strain levels ($\varepsilon_0 \leq 15\%$), equilibrium stresses ended up close to NC $K_0$ line
- Relaxation from larger strain level ($\varepsilon_0 \geq 25\%$) $\Delta$ structure of clay $\rightarrow$ equilibrium at high $K$.

3) See Sheets E1 and E2 for actual test data (mostly for OCR=1)
   - Fig. 1: $q/k_{oc} v \varepsilon_0$
   - Fig 2: ESP data
   - Fig 3: $q/k_{oc} v \log t_r$
   - Fig 5: Equilibrium stress
5.6 Criteria for High Creep Susceptibility

Fig. 3 Ting et al. (1983) JSE 109(10)

\[ \varepsilon' = \varepsilon \text{ at } t = 1 \text{ min} \ (1/\text{sec}) \]

1) Parameter in not releasted criteria

2) Fig. 3 plots \( \varepsilon' \) at \( t = 1 \text{ min} \) vs. \( \dot{\varepsilon} \) from creep tests on various materials.
   - Honey clay with low creep susceptibility plot to lower right (low \( \varepsilon' \) at high \( \dot{\varepsilon} \))
   - Ice / frozen sand with high creep susceptibility plot to upper left (high \( \varepsilon' \) at low \( \dot{\varepsilon} \))

3) Therefore, materials with high creep susceptibility have a high initial strain rate at low shear stress levels.

4) However, value of \( m \) is still relevant since:
   - High \( m \) → rapid decay in \( \varepsilon' \) with time
   - Low \( m \) → slow " " " "
6. **SUMMARY AND CONCLUSIONS**

6.1 **Measurements of $\dot{u}$**

1) Strain rate sensitivity of saturated cohesion soils ($\dot{u}$ = $\phi$ / $\phi$ / $\phi$ (where $\dot{u}$ is the shear rate, $\phi$ is the angle of internal friction, and $\phi$ is the angle of frictional resistance).)

   - All soils have significant $\dot{u}$ at very fast shear rates (say $\varepsilon > 5-10$%,/hr). $\dot{u}$ may range from < 10% to > 30%/log-cycle probably.
   - Cemented, structured Canadian clays have significant $\dot{u}$ at all shear rates.
   - For "unstructured" clays (like RBB), value of $\dot{u}$ at ambient moderate $\varepsilon$ probably decreases with increasing OCR (Section 4.3).

2) Must consider $\Delta \dot{u}$ ($\sigma$ $\delta$ $\delta$) when comparing $\dot{u}$ data from different types of shear tests:
   - For in-situ tests, $CPTU$ $\tau$ = seconds $\delta$ $PVT$ $\tau$ = minute
   - Lab $UVC$, $\varepsilon$ = 1%/min $\rightarrow$ $\tau$ = minute
   - Lab $CKU$, $\varepsilon$ = 0.5%/hr $\rightarrow$ $\tau$ = hours.

3) For SHANSEP/Recompression CKU testing programs, many may use lab values:
   - $TX$ $\varepsilon$ = 0.5%/hr
   - $DSS$ $\varepsilon$ = 5%/hr

   Shallow or in most clays at OCR $>$ 1, maybe somewhat unsafe for low OCR clay.

6.2 **Predictions of Undrained Creep**

1) The Atkinson-Stephens 3-parameter eqn. (Section 5.2) is widely used to model primary creep data from lab tests. However, its use to predict in-situ creep is suspect (due to variable parameters with different modes of loading) plus problems with its incorporation in an effective stress model.

2) One probably can assume correspondence between constant $\varepsilon$ tests and creep rupture lab (using $\varepsilon$ in $\dot{u}$), even developing sun log $\dot{u}$ correlations.
6.2 Cont.

3) It is still difficult to predict when undrained creep is likely to cause "excessive" deformation in the field.
   - Refer to Fortt & Ladd (1981) for loading at low Ps's of low Ks soil with long consolidation time
   - Might also run some C.U. creep tests for comparison with data in Fig 3, p21

4) Will a loaded clay undergo undrained creep rupture in the field at a significant time after the end of loading?
   - CCL thinks highly unlikely, but many others will disagree

6.3 Miscellaneous

1) The importance of isotropy in soil remains unclear

2) For NC clays that are still consolidating, use t_c = t_p
   (worst slr. t_c = 1 day) for C.K.U. testing
Normalized Shear Stress and Shear-induced Pore Pressure vs. Strain, OCR = 1 CKuUC Tests, Resedimented BBC

Symbol $\dot{e}_a$(%/hr) Test No.
- 0.051 21
- 0.051 23
- 0.50 13
- 5.0 33
- 49 48
- 49 52

Normalized Shear Stress, $q/vc' = \Delta p/vc'

Normalized Shear Induced Pore Pressure, $D_us/vc' = D_u - D_s$

Axial Strain, $e_a(\%)$

Normalized Effective Stress, $p/vc''$

Peak Shear Stress

Corresponds to Avg. $\theta_{min} = 32.9^\circ \pm 0.95SD$

Figures by MIT OCW.

Normalized Effective Stress Paths, OCR = 1 CKuUC Tests, Resedimented BBC

Normalized Effective Stress Paths, OCR = 2 CKuUC Tests, Resedimented BBC

Adapted from: Sheahan et al. (1996)
Figures by MIT OCW.
Summary plots of Mechanisms: (a) Normalized Shear-induced pore pressure and (b) Friction angle at peak versus strain rate, CKoUC tests, resedimented BBC.

Figures by MIT OCW.
Adapted from: Sheahan et al. (1996)
Creep rate behavior of normally consolidated undisturbed Haney clay.

Figure by MIT OCW.

\[ q = \frac{(\sigma_1 - \sigma_3)}{\sigma_{vc}} \]

Axial strain until minimum strain rate as a function of creep stress.

Figure by MIT OCW.
Results of unconfined (uniaxial) compressive creep testing of polycrystalline ice. (data by Jacka, see Lile 1979).

\[ \dot{\varepsilon}_m = B \dot{\varepsilon}_m^\gamma \]

\[ e_m \sim 1\% \]

\[ e_m \sim 2.7 \pm 0.5\% \]

Summary of minimum creep rate: Correlations of time to minimum for various materials

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Testing</th>
<th>Reference</th>
<th>B*</th>
<th>( \dot{\varepsilon}_m )</th>
<th>( \dot{\varepsilon}_m^\gamma )</th>
<th>( \dot{\varepsilon}_m^\gamma )</th>
<th>No. Tests</th>
<th>( e_m (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20% Si MFS</td>
<td>Uniaxial</td>
<td>Martin</td>
<td>2.8 x 10^{-3}</td>
<td>-1.2</td>
<td>0.987</td>
<td>7</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>40% Si MFS</td>
<td>Uniaxial</td>
<td>Ting &amp; Load (1981)</td>
<td>4.2 x 10^{-3}</td>
<td>-1.2</td>
<td>0.993</td>
<td>40</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>100% Si MFS</td>
<td>Uniaxial</td>
<td>Jacka, in Lue (1979)</td>
<td>8.1 x 10^{-3}</td>
<td>-1.2</td>
<td>0.991</td>
<td>28</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Ice</td>
<td>Uniaxial</td>
<td>Jacka, in Lue (1979)</td>
<td>7.9 x 10^{-3}</td>
<td>-0.8</td>
<td>0.987</td>
<td>7</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Ice</td>
<td>Uniaxial</td>
<td>Martin (1972)</td>
<td>6.5 x 10^{-3}</td>
<td>-1.0</td>
<td>0.996</td>
<td>8</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Unfrozen Hanchester Fine Sand</td>
<td>CIUC</td>
<td>Campanella &amp; Void (1974)</td>
<td>1.3 x 10^{-3}</td>
<td>-0.9</td>
<td>0.997</td>
<td>8</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

Figures by MIT OCW.
Influence of rate strain on undrained stress-strain behavior in constant rate of strain shear.

Strain rate dependence of undrained strength in constant rate of strain shear and constant stress creep.

Variation of creep rate with time in constant stress creep.
Stress-strain curves, relaxation versus constant strain rate CKoUC tests, resedimented BBC: OCR = 1

Effective stress paths, relaxation versus constant strain rate CKoUC tests, resedimented BBC: OCR = 1

Figures by MIT OCW.

Relaxation data from CKoUC tests on RBBC

Adapted from: Sheahan et al. (1994)
Shear stress decay with time, CKoUC relaxation tests on resedimented BBC: OCR = 1

Stabilized stress states at the end of relaxation phases, CK₀UC relaxation tests on resedimented BBC.

Adapted from: Sheahan et al. (1994)